

FLAVOUR SYMMETRY BREAKING IN THE POLARIZED NUCLEON SEA

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After a brief review on flavour symmetry breaking (FSB) in the unpolarized nucleon sea, we discuss theoretical predications for FSB in the polarized nucleon sea from meson cloud and ‘Pauli blocking’.

1 Flavour symmetry breaking in the unpolarized nucleon sea

The possible breaking of parton model symmetries by the nucleon’s quark distribution functions has been a topic of great interest since the experimental discoveries that the Ellis-Jaffe and Gottfried sum rules are violated. In particular, the flavour asymmetry in the nucleon sea ($\bar{d} > \bar{u}$) has been confirmed by several experiments¹. This asymmetry can be naturally explained in the meson cloud model², in which the physical nucleon can be viewed as a bare nucleon plus some meson-baryon Fock states which result from the fluctuation $N \rightarrow MB$,

$$|p\rangle_{\text{phys.}} = |p\rangle_{\text{bare}} + |\pi N\rangle + |\pi\Delta\rangle + \dots \quad (1)$$

The valence anti-quark in the meson contributes (via a convolution) to the anti-quark distributions in the proton sea. Since the probability of the Fock state $|n\pi^+\rangle$ is larger than that of the $|\Delta^{++}\pi^-\rangle$ state in the proton wave function, the asymmetry $\bar{d} > \bar{u}$ emerges naturally in the proton sea. Another possible source for this asymmetry is that the bare nucleon, $|p\rangle_{\text{bare}}$ may have an intrinsic asymmetry associated with it. According to the Pauli exclusion principle, the $d\bar{d}$ is more likely to be created than the $u\bar{u}$ pair since there are two valence u quarks and only one valence d quark in the proton. So there is a small excess of $d\bar{d}$ pairs over $u\bar{u}$ pairs. This asymmetry has also been studied in chiral quark model³, the chiral quark-soliton model⁴, and the instanton model⁵. It was shown by Melnitchouk, Speth and Thomas⁶ that by using the meson cloud model together with the Pauli blocking, the data for both the ratio $\bar{d}(x)/\bar{u}(x)$ and difference $\bar{d}(x) - \bar{u}(x)$ can be described reasonably well, while using one of these effects will not (see Fig. 1). About half of the asymmetry can be attributed to the meson cloud and the other half to the Pauli blocking. We would like to point out that the data that were compared with is the E866 data in 1998. Recently E866 collaboration reported its improved measurements⁷

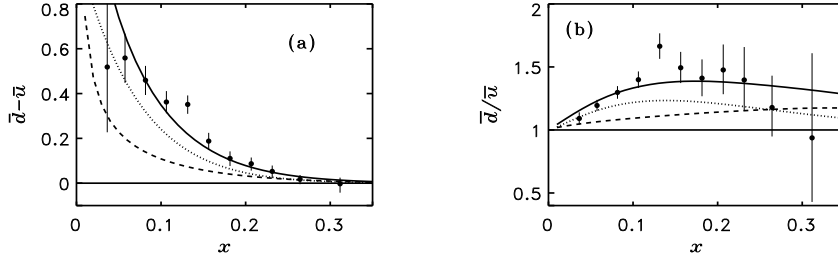


Figure 1: Contributions from pions with $\Lambda_{\pi N} = 1$ GeV and $\Lambda_{\pi\Delta} = 1.3$ GeV (dashed) and from antisymmetrization (dotted) to the (a) $\bar{d} - \bar{u}$ difference and (b) \bar{d}/\bar{u} ratio, and the combined effect (solid). Taken from Phys. Rev. D **59**, 014003 (1998).

in which the statistics are improved and the measured x -range is extended to lower x (from 0.036 to 0.026). An interesting point is that comparing with the previous results, the ratio for x being 0.315 is pushed down from about 0.9 to about 0.4 and the difference $\bar{d} - \bar{u}$ becomes negative, while the other data remain nearly unchanged. So for the last data point in large x in Fig. 1 the theoretical predications will be well outside the error bars. More studies are needed in theoretical calculations and experimental measurements.

2 Flavour symmetry breaking in the polarized nucleon sea

Recently there has been increasing interest in the question of whether this asymmetry extends also to the polarized sea distributions *i.e.* $\Delta\bar{d}(x) \neq \Delta\bar{u}(x)$? Such a polarized sea asymmetry would make a direct contribution to the Bjorken sum rule. Although well established experimental evidence for a polarized sea asymmetry is still lacking, some experimental studies have been done⁸. Moreover several parameterizations⁹ for the polarized parton distributions arising from fits of the world data from polarized experiments leave open the possibility of this asymmetry. There have also been some theoretical studies on this asymmetry. A much larger asymmetry in the polarized sea distributions than that in the unpolarized sea distributions is predicted in the chiral quark-soliton model (using the large- N_C limit)¹⁰. Such sizeable asymmetries would make an important contribution (around 20%) to the Bjorken sum rule. This asymmetry has also been studied by considering the ρ meson cloud in the meson cloud model¹¹. The prediction for $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ is more than one order of magnitude smaller than the result from the chiral quark-soliton model.

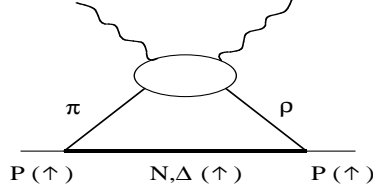


Figure 2: Schematic illustration of interference contributions to the polarized anti-quark distributions.

More theoretical calculations can be found in reference¹². Here we report a study¹³ on the flavour asymmetry of the non-strange polarized anti-quarks using the meson cloud model and ‘Pauli blocking’.

2.1 FSB in the meson cloud model

It was assumed in the meson cloud model (MCM) that the lifetime of a virtual baryon-meson Fock state is much larger than the interaction time in the deep inelastic or Drell-Yan process, thus the quark and anti-quark in the virtual meson-baryon Fock states can contribute to the parton distributions of the nucleon. For polarised parton distributions in the model it is necessary to include all the terms which can lead to the same final state¹⁴. This allows the possibility of interference terms between different terms in the nucleon wavefunction Eq. (1). For polarised anti-quark distributions the interference will be between terms with different mesons and the same baryon e.g. $N\pi$ and $N\rho$ (see Fig. 2). We will consider the fluctuations $p \rightarrow N\pi, N\rho, N\omega$ and $p \rightarrow \Delta\pi, \Delta\rho$. The fluctuation $p \rightarrow \Delta\omega$ is neglected because of isospin conservation. The flavour asymmetry is studied by calculating the difference $x(\Delta\bar{d} - \Delta\bar{u})$ which turns out to be

$$\begin{aligned}
 x(\Delta\bar{d} - \Delta\bar{u}) = & \left[\frac{2}{3}\Delta f_{\rho N/N} - \frac{1}{3}\Delta f_{\rho\Delta/N} \right] \otimes \Delta v_\rho \\
 & + \left[-\Delta f_{(\rho^0\omega)p/p} + \frac{2}{3}f_{(\pi\rho)N/N}^0 - \frac{1}{3}f_{(\pi\rho)\Delta/N}^0 - f_{(\pi^0\omega)p/p}^0 \right] \otimes \Delta v_\rho \\
 = & \Delta f_\rho \otimes \Delta v_\rho + \Delta f_{int} \otimes \Delta v_\rho.
 \end{aligned} \tag{2}$$

where Δv_ρ is the polarized parton distribution of the ρ meson, $\Delta f_{(V_1 V_2)B/N} = f_{(V_1 V_2)B/N}^1 - f_{(V_1 V_2)B/N}^{-1}$ is the polarized fluctuation function and $f_{(M_1 M_2)B/N}^\lambda = \sum_{\lambda'} \int_0^\infty dk_\perp^2 \phi_{M_1 B}^{\lambda\lambda'}(y, k_\perp^2) \phi_{M_2 B}^{*\lambda\lambda'}(y, k_\perp^2)$ is the helicity dependent fluctuation function. $\phi_{MB}^{\lambda\lambda'}(y, k_\perp^2)$ is the wave function of the Fock state containing a meson

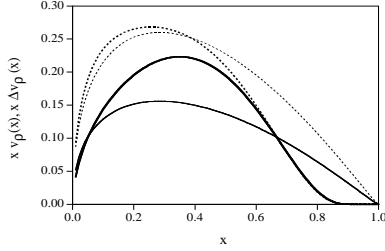


Figure 3: The polarized and unpolarized valence quark distributions of the ρ meson at $Q^2 = 4 \text{ GeV}^2$. See the text for more explanations.

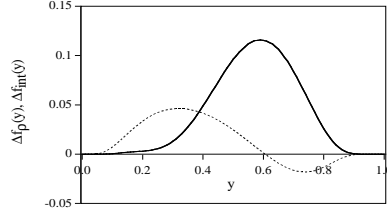


Figure 4: The polarized fluctuation functions Δf_ρ (the solid curve) and the interference term Δf_{int} (the dashed curve). $\Lambda_{oct} = 1.08 \text{ GeV}$, $\Lambda_{dec} = 0.98 \text{ GeV}$.

(M) with longitudinal momentum fraction y , transverse momentum \mathbf{k}_\perp , and helicity λ , and a baryon (B) with momentum fraction $1 - y$, transverse momentum $-\mathbf{k}_\perp$, and helicity λ' . The first term in Eq. (2) is the same as the result given in ¹¹. The second term in Eq. (2) is the interference contribution. We note that there are no contributions directly from the ω meson due to its charge structure.

We adopt two prescriptions for Δv_ρ (see Fig. 3): (i) employing the MIT bag model calculation, $\Delta v_\rho^{MIT}(x)$ (the thick solid curve) and (ii) adopting the ansatz $\Delta v_\rho(x) = 0.6v_\pi(x)$ (the thin solid curve) as in ¹¹. The parameters of the MIT bag model calculation are fixed by fitting the calculated unpolarized parton distribution of the ρ meson (the thick dashed curve) to the Gluck-Reya-Schienbein parameterization ¹⁵ for the valence parton distribution of the pion (the thin dashed curve). The first moment of $\Delta v_\rho^{MIT}(x)$ is found to be about 0.60 at $Q^2 = 4 \text{ GeV}^2$, which is in agreement with the lattice value ¹⁶ of 0.60. It can be seen that the distribution $0.6xv_\pi(x)$ is smaller than $x\Delta v_\rho^{MIT}(x)$ in the intermediate x region, although both distributions satisfy the same normalization condition. Also the bag model calculated parton distribution has a different x -dependence from the unpolarized distribution.

The fluctuation functions Δf_ρ and Δf_{int} in Eq.(2) are calculated by using time-ordered perturbation theory in the infinite momentum frame ^{13,17}. (see Fig. 4. Λ is a cut-off parameter in the phenomenological form factor introduced to describe the unknown dynamics in the fluctuation $N \rightarrow MB$.) It can be seen that the maximum of Δf_{int} is about 40% that of Δf_ρ . So the interference contribution to $x(\Delta \bar{d} - \Delta \bar{u})$ will not be negligible, although Δf_{int} changes sign from positive to negative at about $y = 0.6$.

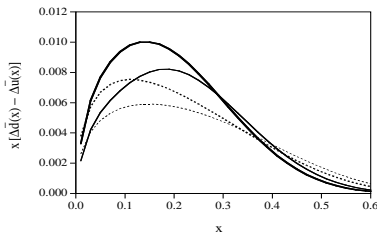


Figure 5: The flavour asymmetry of the anti-quark in the proton. The solid curves are the predictions using $x\Delta v_\rho^{MIT}$, while the dashed curves are obtained by using $0.6xv_\pi(x)$. The thin curves are the results without interference contribution while the thick curves are the results with interference contribution.

The results for $x(\Delta\bar{d} - \Delta\bar{u})$ are shown in Fig. 5. The interference effect increases sizably the predictions for the flavour asymmetry, and pushes the curves towards the small x region due to Δf_{int} being peaked at smaller y ($y_{max} \simeq 0.3$) than the Δf_ρ ($y_{max} \simeq 0.60$). Also the calculations with $x\Delta v_\rho^{MIT}(x)$ are larger than that with $0.6xv_\pi(x)$ in the intermediate x region, and have their maxima at larger x .

The integral

$$\begin{aligned} I_\Delta &= \int_0^1 dx [\Delta\bar{d}(x) - \Delta\bar{u}(x)] \\ &= \int_0^1 dx \Delta v_\rho(x) \int_0^1 dy [\Delta f_\rho(y) + \Delta f_{int}(y)] \end{aligned} \quad (3)$$

will be the same for both models for the polarized parton distribution of the ρ as they have the same first moment for the polarized distribution. We find the integral to be 0.023 (0.031) without (with) the interference terms for $\Lambda_{oct} = 1.08$ GeV and $\Lambda_{dec} = 0.98$ GeV. The interference effect increases the integral by about 30%. The prediction for the integral I_Δ has a strong dependence on the cut-off parameters Λ_{oct} and Λ_{dec} . For example, the results with (without) interference contribution vary from 0.0043 (0.0027) to 0.033 (0.020) for the cut-off parameters changing from $\Lambda_{oct} = \Lambda_{dec} = 0.8$ GeV to 1.10 GeV. Clearly these values obtained using the meson cloud model are very different from those obtained using the chiral quark-soliton model¹⁰ which have a magnitude of around 0.3. It is interesting that both models agree well with the experimental data for the unpolarized asymmetry, yet predict very different results for the polarized asymmetry. As the magnitude of the predicted polarized asymmetry appears to be fairly natural in each of these models, experimental

data will provide a valuable test of these models, and give insight into the relation between helicity dependent and helicity independent observables in quark models.

2.2 FSB from ‘Pauli blocking’

Now we consider the contribution to the asymmetry arising from ‘Pauli blocking’ effects^{6,18,19}. In a model such as the bag model, where the valence quarks are confined by a scalar field, the vacuum inside a hadron is different from the vacuum outside. This manifests itself as a distortion in the negative energy Dirac sea, which is full for the outside (or free) vacuum, whereas there will be empty states in the Dirac sea of the bag. To an external probe this change in vacuum structure appears as an intrinsic, non-perturbative sea of $q\bar{q}$ pairs. This change in the vacuum is similar to the change in the Fermi-Dirac distribution when the temperature is raised above absolute zero. Now when a quark is put into the ground state of the bag it will have the effect of filling some of the empty negative energy states in the sea of the bag vacuum. The reason for this is that the ground state wavefunction can be written as a wavepacket in terms of plane wave states of positive and negative energy, with the energy distribution of the wavepacket centred at the ground state energy eigenvalue, but with non-zero contributions from negative energy plane waves. Hence the presence of a quark in the bag ground state lowers the probability of a negative energy state being empty, which is the same as lowering the probability of finding a positive energy antiquark. As the proton consists of two up quarks and one down quark, the probability of finding a \bar{u} antiquark is reduced more than the probability of finding a \bar{d} antiquark *i.e.* $\bar{d} > \bar{u}$.

When we include spin in the analysis of Pauli blocking, we find that putting a spin up quark into the bag ground state has the effect of filling some of the negative energy spin up quark states in the bag vacuum, which is equivalent to lowering the probability of finding a positive energy spin down antiquark. As the $SU(6)$ wavefunction of the spin up proton is dominated by terms with the two up quarks having spin parallel to the proton spin and the down quark having spin anti-parallel, Pauli blocking predicts that the probabilities of finding spin down \bar{u} antiquarks and spin up \bar{d} antiquarks are reduced *i.e.* $\bar{u}^\uparrow > \bar{u}^\downarrow$, $\bar{d}^\downarrow > \bar{d}^\uparrow$ or $\Delta\bar{u}(x) \geq 0$, $\Delta\bar{d}(x) \leq 0$.

We estimate the contribution of the Pauli blocking effect to the polarized asymmetry using the Adelaide group’s argument for calculating parton distributions in the bag model. It was found

$$\bar{d}(x) - \bar{u}(x) = F_{(4)}(x), \quad \Delta\bar{d}(x) - \Delta\bar{u}(x) = -\frac{5}{3}G_{(4)}(x). \quad (4)$$

where $F_{(4)}(x)$ and $G_{(4)}(x)$ are the spin independent and spin dependent kinematic integrals over the momentum of the intermediate four quark state. As $G_{(4)}(x)$ is positive at all x , Pauli blocking gives a negative contribution to the spin dependent flavour asymmetry in the sea, whereas the meson cloud contribution tended to be positive. Also noting that as $F_{(4)}(x) \geq G_{(4)}(x)$, we can integrate over all x and then obtain an upper limit for the size of the Pauli blocking contribution to the spin dependent asymmetry in terms of the contribution to the spin independent asymmetry:

$$-\int_0^1 dx [\Delta \bar{d}(x) - \Delta \bar{u}(x)] \leq \frac{5}{3} \int_0^1 dx [\bar{d}(x) - \bar{u}(x)]. \quad (5)$$

As an estimate for the integral on the rhs of Eq. (5) we may use the value of 0.07 given by the analysis of reference⁶. This then gives an upper limit of about 0.12 for the magnitude of the integral over the polarized asymmetry. In the bag model, the ratio $G_{(4)}(x)/F_{(4)}(x)$ varies from about 0.8 at low x to unity at large x , which gives us a value of about -0.09 for the integrated polarized asymmetry. While these values are calculated at some scale appropriate to the bag model, the values of the integrals are not much affected by evolution up to experimental scales, so we expect the relation between polarized and unpolarized sea asymmetries to be approximately correct at all scales. The value of the Pauli blocking contribution to the integrated polarized asymmetry is much larger than that we have calculated in the meson cloud model, in contrast to approximate equality in the unpolarized case. Thus the experimental observation of any asymmetry in the polarized sea distributions is much more a test of the Pauli blocking hypothesis than of the meson cloud model. We estimate that the contribution to the Bjorken sum rule from Pauli blocking plus meson cloud effects is about 5-10% of the value of the sum rule.

3 Summary

We report a study on the flavour asymmetry of the non-strange polarized anti-quarks using the meson cloud model and ‘Pauli blocking’. In the meson cloud model, we have included the contributions from both the vector meson cloud and the interference terms between pseudoscalar and vector mesons. It was found that the interference terms can provide sizable contribute to the asymmetry in the intermediate x region. We have also discussed the effect of ‘Pauli blocking’ on the asymmetry, and have seen that this effect gives a larger contribution to the asymmetry than meson cloud effects, in contrast to the unpolarized case.

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